COMPLETE SPECIFICATION.

Pressure Wave Attenuator.

We, GENERAL MOTORS CORPORATION, a Company incorporated under the laws of the State of Delaware, in the United States of America, of Grand Boulevard, in the
5 City of Detroit, State of Michigan, in the United States of America (Assignees of GERARD TIMOTHY KLEES), do hereby declare the invention, for which we pray that a patent may be granted to us, and the
10 method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to attenuator devices for attenuating periodic pressure waves
15 in fluid media in a conduit, by means of pressure wave interference.

The invention can be applied to many forms of apparatus for the elimination of noise in fluid circuits.

20 Attenuators according to this invention are of particular utility in the elimination of objectionable noises or vibrations created by certain of the operating components of a motor vehicle, particularly the so-called
25 "rasp" associated with a vehicle power steering gear.

Power steering "rasp" is the result of the steering column and other associated structure being excited by the periodic pressure
30 pulsations of the power steering pump, and it is generally manifested to the driver as objectionable vibration at the steering wheel, particularly during engine idling conditions.

The scope of the monoply is defined by
35 the appended claims; and how the invention can be performed is hereinafter particularly described with reference to the accompanying drawings in which:—

Figure 1 is an explanatory diagram of a
40 known form of attenuator of the pressure wave interference type;

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Figure 2 is another known form of such an attenuator;

Figure 3 is a section of one form of attenuator according to this invention; 45

Figure 4 is a section of a second form of a attenuator according to this invention;

Figure 5 is a diagrammatic view of a vehicle power steering system incorporating a third form of a attenuator according to 50 this invention;

Figure 6 is an enlarged broken view of a portion of the system shown in Figure 5;

Figure 7 is a view similar to Figure 6 of a fourth form of attenuator according to 55 this invention; and

Figure 8 is a graph illustrating the operating characteristics of an attenuator device according to this invention.

In Figure 1 one and a half wavelength 60 side-branch tube 10 is connected to a conduit 12 for attenuation of periodic pressure wave motion transmitted through the medium contained therein. Such a wave when reaching the inlet of tube 10, divides 65 and travels over the lengths of the tube 10 and the conduit 12 to unite at the output of the tube 10 substantially one-half wavelength, or 180°, out of-phase, ideally to resulting in a pressure disturbance of zero 70 amplitude. For example, for a length L1 of traversed conduit 12 $L_1 = \lambda$, this cancellation is effected by setting tube 10

to a length $L = L_1 + \dfrac{\lambda}{2} = \dfrac{3\lambda}{2}$.

Figure 2 illustrates a quarter-wave side- 75 branch tube type of attenuator, wherein the pressure disturbance at the inlet of the side-branch tube 14 travels a quarter wavelength to the closed end of the tube, is reflected therefrom, and travels back another quarter 80 wavelength so as to unite with the pressure

wave in conduit 12 one-half wavelength, or 180°, out-of-phase therewith. In this case tube 14 is set to a length $L = \dfrac{\lambda}{4}$. The wavelength λ for a periodic wave of a given frequency f and propagated with the speed of sound c of the medium is determined according to the relation

$$\lambda = \frac{c}{f} \qquad (1)$$

The tuning of the devices such as shown in Figures 1 and 2 have usually been determined on the assumption that the walls of the conduit are sufficiently rigid that yielding of the conduit walls may be neglected.

The present invention instead of avoiding transverse momentum flux effects, employs these effects to advantage in reducing the size to which an attenuating device must be tuned to a given frequency.

The transverse momentum flux effects, and their influence on the longitudinal propagation rate in the medium are ultimately a result of the work done on the walls of the surrounding conduit, as determined primarily according to the elasticity of the wall material. The speed of sound c within a conduit made of a particular material is thus directly related to its elasticity; and it has been theoretically and experimentally determined that this relation may be described as:—

$$\frac{c}{V_c} = \frac{1}{\sqrt{1 + \dfrac{KD}{Et}}} \qquad (2)$$

where

V_c is the normal or characteristic propagation rate of a spherical wave in an unbounded bulk of the medium, or of a plane wave in a conduit of infinite rigidity;

K is the bulk modulus of elasticity of the medium;

D is the inside diameter of the conduit;

E is Young's modules of radial elasticity of the conduit wall; and

t is the thickness of the conduit walls.

If $\dfrac{KD}{Et}$ is large compared with unity, the effect is to substantially decrease the speed of sound from that in a bulk medium, or from that in a rigid conduit.

In medium grade oil, for example, having a normal speed of sound $c = 4370$ ft./sec., and a bulk modulus $K = 220,000$ p.s.i., a pressure wave through a steel conduit containing such oil and having a Young's modulus $E \simeq 3 \times 10^7$ p.s.i. and a ratio $\dfrac{D}{t}$ 11.5, would propagate the wave at about 4300 ft./sec. However, a rubber conduit of the same dimensions but having a Young's modulus $E \simeq 800$ p.s.i. would propagate at about 77 ft./sec.

According to this invention when applying these considerations to an attenuator, the physical size to which the side-branch tube must be tuned for elimination of a given frequency is greatly reduced by selection of the properties of the side-branch wall material. If for example, the tube 10 is of Figure 1 steel, and contains medium grade oil, and is to be tuned for elimination of a frequency of about 120 cycles per second, the length to which the tube should be tuned to be $L = \dfrac{3\lambda}{2} = \dfrac{(3)\,(4300)}{(2)\,(120)} = 54$ feet. If however, the tube is rubber, the length of the tube is reduced to $\dfrac{(3)\,77}{(2)\,(120)}$ or 0.96 feet.

Such an attenuator device is shown in Figure 3, wherein both the main conduit and the side-branch tube 16 are made of rubber and the main conduit section is of a length $L_1 = \lambda = .64$ feet and the tube 16 is of a length $L = \dfrac{3\lambda}{2} = .96$ feet.

For the quarter-wave side-branch tube 14 of Figure 2, a steel tube would be 9 feet long; but if made of rubber would be only 2 inches long. Such an attenuator is shown in Figure 4, the rubber side-branch tube 18 being set to a quarter wavelength.

In general for these attenuators with side-branches set either to a quarter wavelength or to a half wavelength, or odd multiples of either, then solving equation (2) for c, and substituting into equation (1) an attenuator according to this invention is set according to the equation

$$L = \left[\frac{n}{4}, \frac{m}{2}\right] \frac{V_c}{f\sqrt{1 + \dfrac{KD}{Et}}} \qquad (3)$$

where $\dfrac{n}{4}$ and $\dfrac{m}{2}$ are series multipliers respective to the quarter and half wave modes of side-branch operation, and where both n and m equal any odd integer.

A particular application of this principle to a pressure wave interference attenuator

for use in a vehicle power steering system, will now be described with reference to Figures 5 to 8 of the drawings.

Figure 5 illustrates a conventional power 5 steering system including a pump 20 drawing oil or other fluid from a reservoir 22 and connected through a tube 24 to the control valve of a steering gear 26. A piston type fluid motor within gear 26 is opera- 10 tively connected to a pitman arm 28 which is connected to the dirigible wheels of the vehicle through linkage in the usual way. The control valve of gear 26 is connected to a steering shaft assembly 30 having a 15 manual steering wheel 32. In such power steering systems the pressure pulsations generated by the pump are communicated throughout the fluid in sufficient strength to excite the steering shaft 30 and associated 20 structure into substantial vibration or "rasp" which is manifested to the driver and is most objectionable at low engine speeds.

As the most objectionable "rasp" condi- 25 tions occur at a substantially fixed pump speed, an attenuator according to this invention is employed to eliminate such pulsations. In choosing a specific configuration of the attenuator consideration is given also 30 to minimum pressure loss, maximum compactness, and suitability for use in fluid systems working at pressure of the order of 1,000 p.s.i. A coaxial tube arrangement in the supply tubing assembly 24 (Figure 6) 35 performs both the function of supplying pressurized fluid from the pump 20 to gear 26, and acting as an attenuator according to this invention.

The assembly 24 comprises a reinforced 40 rubber hose 34 having an end fitting 36 for connection to pump 20, and an end fitting 38 for connection to the supply port of gear 26. Each assembly 36 and 38 includes cylindrical socket 40 for encircling the end of 45 hose 34, and a coaxial tube 42 inserted in the hose. Each socket 40 is crimped on to the end of hose 34.

Within tube 42 is secured one end of a flexible tube 46, its other end having an 50 open end cap 48 which prevents abrasion of hose 34.

The annular cavity 50 formed intermediate hose 34 and tube 46 acts as a quarter wave attenuator side-branch tuned to a 55 length L. Pressure waves originating from the pump travel through tubes 42 and 46 to pass into a fluid-filled chamber 52 within hose 34. A wave, on leaving the tube 46 and passing into chamber 52, radiates 60 spherically downstream towards gear 26 also upstream into annular cavity 50. The upstream wave is reflected off the inner end 54 of fitting 36, and again traverses the length of the annular cavity downstream to 65 "interference" within chamber 52 with the

wave leaving tube 46, substantially 180° out-of-phase. The wave is thus substantially zero, and the pressure waves from the pump 20 are effectively eliminated before reaching gear 26 and its associated struc- 70 ture.

Referring now to Figure 8, which shows characteristics of the attenuator shown in Figure 6, at the rasp frequency f_r, attenuation as high as 20 db is realised, the phase 75 shift being about 90°.

In experimentation, a device as shown in Figure 6 and using a standard fabric reinforced rubber hydraulic hose produced an attenuation of 20 db at a frequency of 140 80 c.p.s., with a length L of only about 14 inches.

Similar peaks of attenuation and phase shift are seen to occur at odd multiples of f_r. The fairly broad bands of attenuation 85 centering at f_r and at the odd multiples thereof are believed to arise from additional effects in gear 26, or by the liquid volume in chamber 52. In practice, best results are obtained for the frequencies considered 90 when the downstream end of tube 46 at end cap 58 is spaced approximately one inch from the flange of tube 42.

Although the attenuator of Figure 6 has a cap on tube 46 downstream from pump 95 20, it may be at the upstream end.

The operating characteristics shown in Figure 8, particularly the band-broadening effects mentioned above, will vary slightly with variations in the size of chamber 52, 100 and with the cross-sectional area of cavity 50. These band-broadening effects may result in a lengthening or a shortening of the hose under pressure changes therein. The best nominal length of hose 34 has there- 105 fore to be determined in practice. Predictable variations occur as the elasticity of hose 34 changes with the static pressure of the liquid. Further, in tuning cavity 50 to a length appropriate for quarter wave opera- 110 tion with respect to f_r, variations in the operation of the attenuator will occur if some additional structure is interposed between the inlet of gear 26 and fitting assembly 38 which causes reflections effect- 115 ing the wave phase relationships sought.

Nevertheless it is manifest that a greatly improved attenuator results from forming the side-branch of coaxial elastomeric and metal tubes, the rubber hose 34 enabling a 120 very short side-branch or cavity 50 of length L as determined according to equation (3) above.

The construction shown in Figure 7 is tuned to approximately twice the length of 125 the quarter wave device of Figure 6. Incoming pulse is transmitted through an inner tube 56 apertured at 58 adjacent the upstream end to permit communication of the pressure wave to an annular cavity 60 130

formed intermediate tube 56 and the hose 62. The pressure wave travelling downstream through cavity 60 lags behind the wave travelling through tube 56 by substantially 180° or one-half wavelength.

Thus, the time lag $T = \dfrac{L_o}{c_o} - \dfrac{L_i}{c_i} = \dfrac{1}{2f}$, where

f is the frequency,

L is the length of a passage between the points of path separation and subsequent joining,

c is the speed of sound,

and the subscripts i and o denote the inner and outer passages respectively of tube 56 and cavity 60. In forming the device into a coaxial tube arrangement, $L_i = L_o = L$. Thus, $L = \dfrac{c_o c_i}{2f c_i - c_o}$. Assuming, however, that $c_i \gg c_o$ where tube 56 is of substantially rigid material and hose 62 is highly elastic, this equation may be reduced to $L = \dfrac{c_o}{2f}$, with c_o being determined on the properties and dimensions of the hose and medium according to equation (2) given above. Thus, this half-wave Quincke attenuator is substantially twice the length of the device of Figure 6, and is in accordance with the equation:—

$$L = \dfrac{V_o}{2f\sqrt{1 + \dfrac{KD}{Et}}} \qquad (4)$$

As the side-branch conduit of the Quincke attenuator of this invention may be constructed of many types of elastomeric material, including those which are non-homogeneous, the modulus E in equations (3) and (4) above may represent either Young's modulus, or an equivalent modulus of radial elasticity as determined empirically for a conduit of a given material by dividing a unit circumferential stress resulting from unit pressure input by unit circumferential strain, as measured by unit volume increase. Further, equation (2) above, representing the work done on the fluid and on a conduit of elastomeric material, does not exhaustively represent the principles of operation of this invention; similar equations can be applied of the work done on the conduit is determined not only from the properties of the material, but also from the peculiarities of particular configurations of conduit. Thus, the highly radially flexible side-branch of the attenuator may be obtained, for example, by constructing the side-branch of thin metal material but axially convoluting it in such that it undergoes pronounced radial expansion under the force of the pressure wave motion.

The devices shown and described herein, although specifically applied to the minimisation of power steering rasp, are equally applicable to the minimisation of those in other systems.

WHAT WE CLAIM IS:—

1. A pressure wave interference attenuator comprising a conduit for transmitting said wave, and a side-branch constructed of elastomeric material and communicating with said main conduit, said side-branch being tuned for said interference according to a function of the elasticity of said material.

2. A pressure wave interference attenuator for pressure waves transmitted through fluid media in a main conduit, comprising a side-branch constructed of elastomeric material and communicating with said main conduit, said side-branch being tuned to a length L according to the relation

$$L = \left[\dfrac{n}{4}, \dfrac{m}{2}\right] f\sqrt{1 + \dfrac{V_c}{\dfrac{KD}{Et}}}$$

where n and m each equal any odd integar f is the frequency of said wave motion, V_c is the characteristic speed of sound derived from the adiabatic properties of the fluid in an unbounded bulk state, K is the bulk modulus of elasticity of said fluid, D is the inner diameter of said side-branch, t is the wall thickness of said side-branch, and E is a modulus of elasticity of said material.

3. An attenuator according to claim 1 or 2 in which the main conduit comprises a flexible tube.

4. An attenuator according to any of the preceding claims wherein the main conduit and side-branch are arranged coaxially.
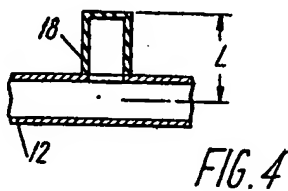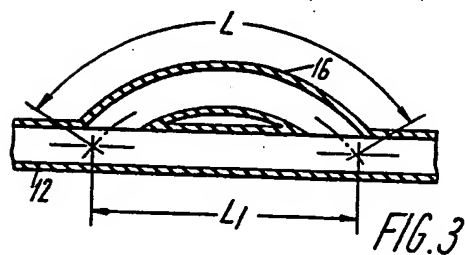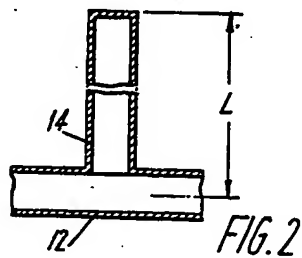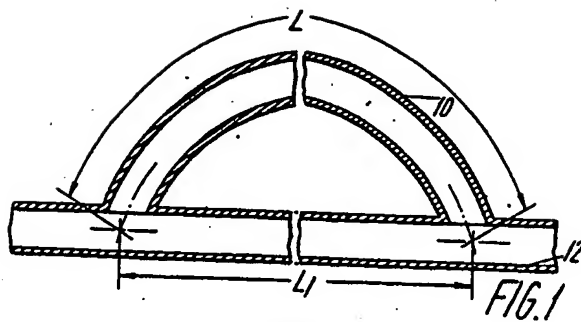
5. An attenuator according to claim 4 tuned to a quarter wave length, wherein the main conduit has a square inner end off which an upstream wave reflects back down stream.

6. An attenuator according to claim 4 tuned to a half wave length, wherein the main conduit inner tube has apertures to provide communication with an annular cavity.

7. A vehicle power steering system, comprising, a fluid motor for steering the wheels of the vehicle, a pump, a conduit connected between said motor and said pump for transmitting fluid under pressure between said motor and said pump, said conduit

including a portion constructed of elastomeric material and forming an attenuator for attenuating pressure waves from said pump, said portion being tuned according to a function of the elasticity of said material.

8. A vehicle power steering system according to claim 7 having an attenuator according to any of claims 1 to 6.

9. A vehicle power steering system, comprising, a source of fluid, a pump, a fluid motor, a hose constructed of elastomeric material, a flexible tubular member arranged coaxially with said hose material, end fittings for connecting one end of said hose to said pump and the other end of said hose to said motor to pass fluid under pressure between said pump and said motor and through said hose member, said hose member and said tubular member forming therebetween an attenuator annular cavity for cancellation of pressure waves from said pump, said cavity being tuned to an effective length according to a function of the elasticity of said elastomeric material, said hose and said tubular member being bodily flexible as a unit to permit installation in a desired curvature between said pump and said motor.

10. A system according to claim 9 wherin said cavity is tuned according to said function of elasticity to a quarter wave length of the pressure wave in said cavity,

wherein one end of said cavity is closed to communication between said members, and wherein said end fitting includes a portion forming a reflective termination.

11. A system according to claim 9 wherin said cavity is tuned according to said function of elasticity to a half wave length of the pressure wave in said cavity, wherein one end of said cavity is open to communication between said members, and wherein the inner one of said members has apertures in its wall adjacent one end of said cavity to provide a half wave sidebranch.

12. An attenuator substantially as hereinbefore particularly described and as shown in Figure 3 of the accompanying drawings.

13. An attenuator substantially as hereinbefore particularly described and as shown in Figure 4 of the accompanying drawings.

14. An attenuator substantially as hereinbefore particularly described and as shown in Figure 6 of the accompanying drawings.

15. An attenuator substantially as hereinbefore particularly described and as shown in Figure 7 of the accompanying drawings.

16. A vehicle power steering system substantially as hereinbefore particularly described and as shown in Figure 5 of the accompanying drawings.
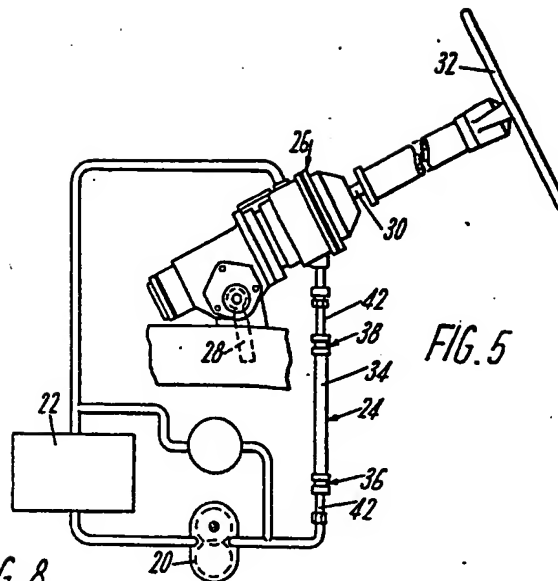
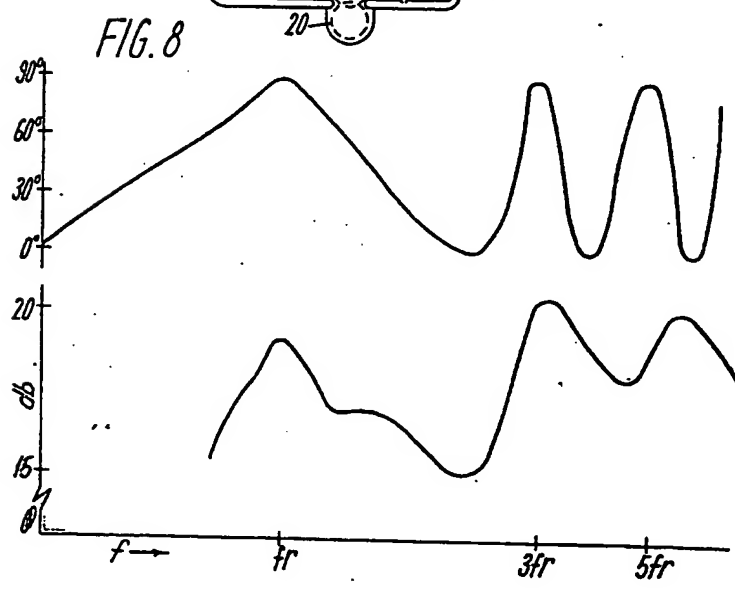E. WILLIAMSON,
Chartered Patent Agent.

FIG.1

FIG.2

FIG.3

FIG.4

FIG.5

32
26
30
28
42
38
34
24
22
36
42
20

FIG.8

90°
60°
30°
0°

20
db
15
θ

f→   fr   3fr   5fr

FIG.6

FIG.7

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2 SHEETS

COMPLETE SPECIFICATION

This drawing is a reproduction of
the Original on a reduced scale
Sheet 2

FIG.5

FIG.6

FIG.7

FIG.8